More AI for Accelerators

Tia Miceli

AI for Accelerators: A Snapshot at Fermilab

14 January 2022

A few more short summaries

- Orbit Alignment at PIP2IT Using Bayesian Optimization

- AI / ML for NuMI Target System Monitoring

- Real-time quench detection

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Orbit Alignment at PIP2IT Using Bayesian Optimization

Pavlo Lyalyutskyy, Eduard Pozdeyev

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Accelerator Tuning: Old Challenge, Novel Approach

Pavlo Lyalyutskyy
Eduard Pozdeyev

- **Tune an accelerator:** Find configurations of beam parameters to optimize beam metrics (energy, beam loss, trajectory, or beam size).

- **Challenges:**

  o Many variables, tens to hundreds degrees of freedom

  o Non-linear, non-independent, non-convex

  o Frequently, manual, not-reliable, non-reproducible

  o Time consuming (tens of minutes to hours)

- **Possible Solution**

  o Automate, speed up, and improve reliability using ML/AI-based algorithms

  o Automated tuning algorithms (e.g., Simplex) exist but will benefit from an "intelligent" approach

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Application:
Beam Trajectory Alignment at PIP2IT

Pavlo Lyalyutskyy
Eduard Pozdeyev

- Beam orbit alignment in PIP2IT using **Bayesian Optimization with Gaussian Processes**

- PIP-II Injector Test (PIP2IT) facility is near-complete Front End of PIP-II accelerator with two first cryomodules

- Beam trajectory is perturbed by misaligned cavities and magnets

  - Measured by **Beam Position Monitors (BPMs)**

  - Orbit is steered by orbit **corrector** magnets

- Task: reduce orbit deviation in BPMs

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Method:
Bayesian Optimization With Gaussian Processes

Pavlo Lyalyutskyy
Eduard Pozdeyev
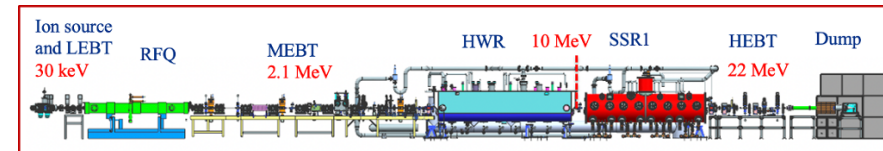
1. Choose a surrogate model and define a **prior**.

$$f(x_{1:k}) \sim \text{Normal}\left(\mu_0(x_{1:k}), \Sigma_0(x_{1:k}, x_{1:k})\right)$$

2. Use Bayes Rule to update our prior to get the **posterior**.

$$f(x)|f(x_{1:n}) \sim \text{Normal}(\mu_n(x), \sigma_n^2(x))$$
$$\mu_n(x) = \Sigma_0(x, x_{1:n})\Sigma_0(x_{1:n}, x_{1:n})^{-1}\left(f(x_{1:n}) - \mu_0(x_{1:n})\right) + \mu_0(x)$$
$$\sigma_n^2(x) = \Sigma_0(x, x) - \Sigma_0(x, x_{1:n})\Sigma_0(x_{1:n}, x_{1:n})^{-1}\Sigma_0(x_{1:n}, x).$$

3. Use an acquisition function $a(x)$ to decide next point to sample.

$$x_t = \text{argmax}_{x \in A} \alpha(x)$$

4. Add newly sampled point to the observations and go to step #2, until convergence.

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Results:
Demonstrated Fast Orbit Alignment in PIP2IT

Pavlo Lyalyutskyy
Eduard Pozdeyev

Convergence with 26 free parameters (degrees of freedom).

Convergence in ~30 steps.
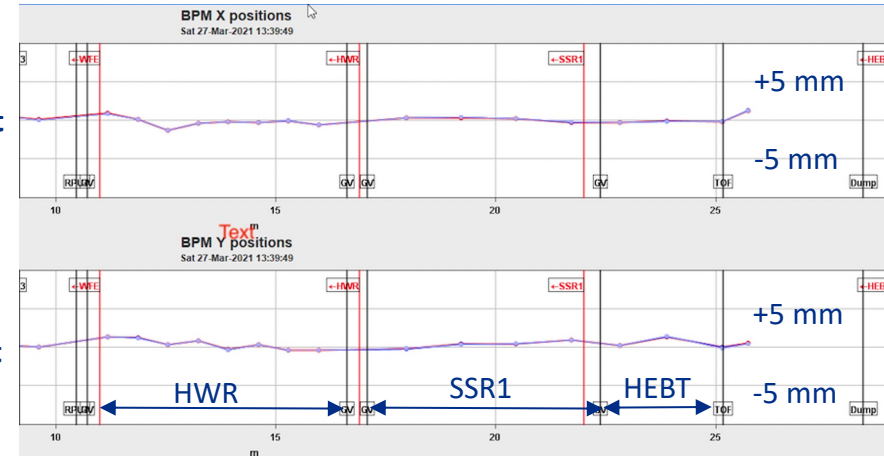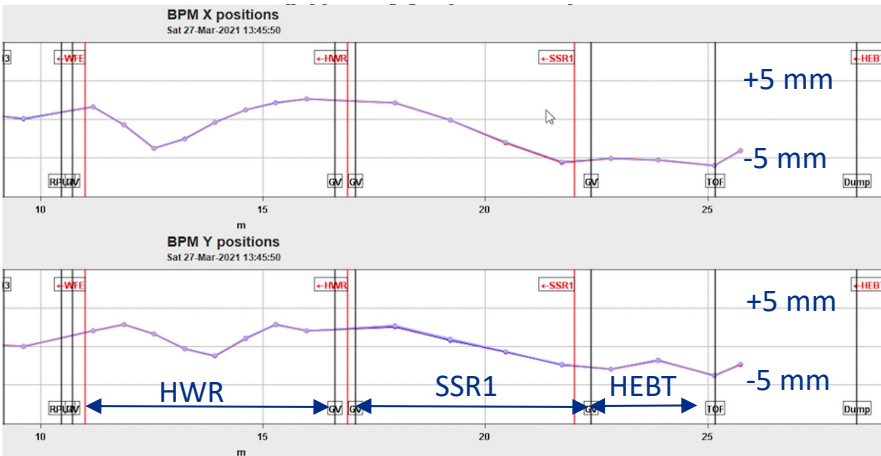
Convergence several times faster than Simplex

Bayesian Optimization, Live Accelerator (26 DOF)
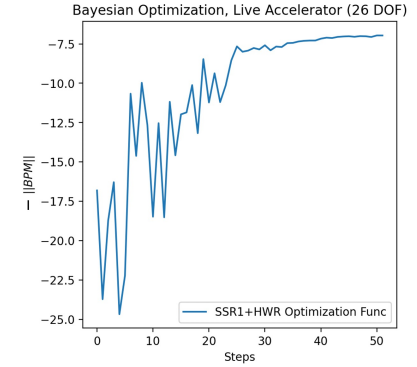
Orbit before correction (not acceptable)

After correction (good)

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Conclusions and Path Forward

- Successful test at PIP-II provided useful experience and pointed out several areas that require additional focus

  - The method works. It converges faster than Simplex, way faster than a human. Reliable.

  - Main effort was to bracket for corrector strength (Too much strength cause beam losses, wrong BPM response, throw off measurements. Too little strength does not allow to reach minimum of orbit deviation.)

- PIP2IT facility was disassembled and stored until PIP-II building is ready

- Path forward

  - More tests at PIP-II planned. Test can be conducted at operating accelerators.

  - If tests are successful, BO-based software will be included in operational, tuning software

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AI / ML for NuMI Target System Monitoring

Athula Wickremashinghe, Katsuya Yonehara

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AI / ML for NuMI Target System Monitoring
Challenge and context

Athula Wickremashinghe,
Katsuya Yonehara

Challenge:

NuMI target system is world's brightest neutrino beam source for neutrino oscillation experiments. The goal of target system AI is predicting a beam related systematic uncertainty for a neutrino flux per beam spill.

Context:

- *The Validation of target system AI (present work)*
  - There are three layers of muon monitors and each monitor provides 9 x 9 pixel image. Our first AI analyzes the image to predict beam position at the target, horn current, and beam intensity per beam spill.
- *Anomaly detection (future work)*
  - Collect muon monitor and other instrumentation signals to catch any accidental changes of beam element (target density deterioration, misalignments of elements, water condensation in the beam line, etc)
- *Prediction of neutrino flux (future work)*
  - Train AI with Monte Carlo simulations to predict a neutrino flux at neutrino detectors by using the observed muon monitor signals

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AI / ML for NuMI Target System Monitoring

Athula Wickremashinghe, Katsuya Yonehara

Approach for solution

- Data samples have been collected from the beam and horn current scans data and the normal operation data for different beam settings

- The optimal neural network model architecture has been searched by following a procedure to obtain the optimal hypeparametes in the selected parameter space

- The model tuning has been done based on the Bayesian optimization algorithm

- Number of hidden layers, nodes, learning rate, activation functions and batch size are optimized base on the model tuning algorithm

An example of optimized NN architecture:

Input pixels = 241(removed 2 bad pixels)

Batch size = 32

Learning rate = 1E-5

Layer (type)	Output Shape	Param #	Activation
dense (Dense)	(None, 480)	116160	Tanh
dense_1 (Dense)	(None, 130)	62530	Sigmoid
dense_2 (Dense)	(None, 135)	17685	Sigmoid
dense_3 (Dense)	(None, 11)	1496	Sigmoid
dense_4 (Dense)	(None, 4)	48	Linear

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AI / ML for NuMI Target System Monitoring

Athula Wickremashinghe,
Katsuya Yonehara

Approach for solution

- An example of a preliminary search of the number of nodes in the hidden layers for learning rate 1E-4 and batch size 64 are sown in the contour plot

- The search is based on the minimum standard error of all 4 output variables

- The contour plot is mapping out the regions based on the high to low values of the standard errors on predictions
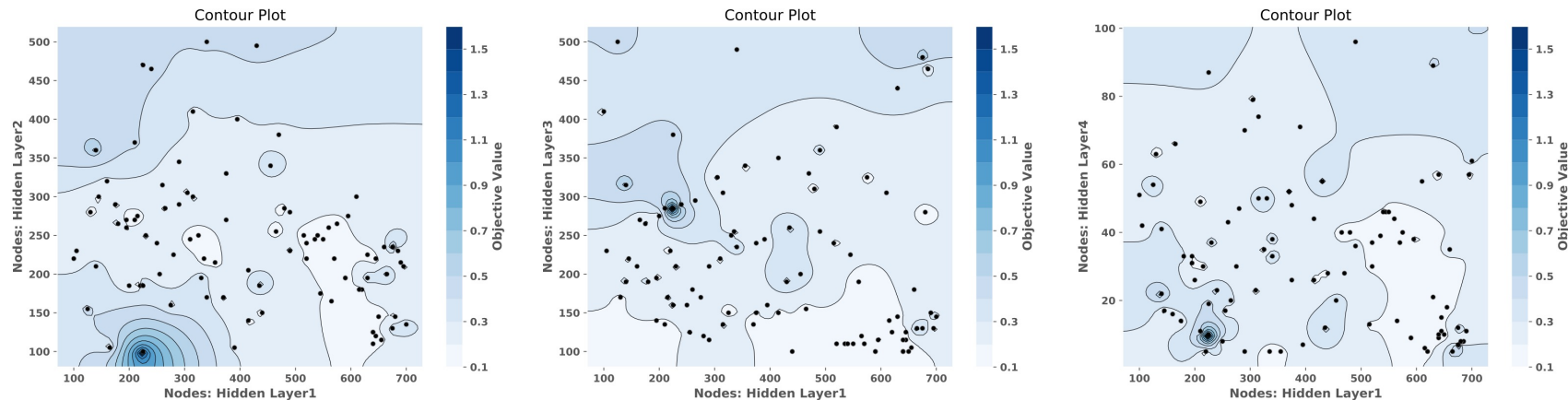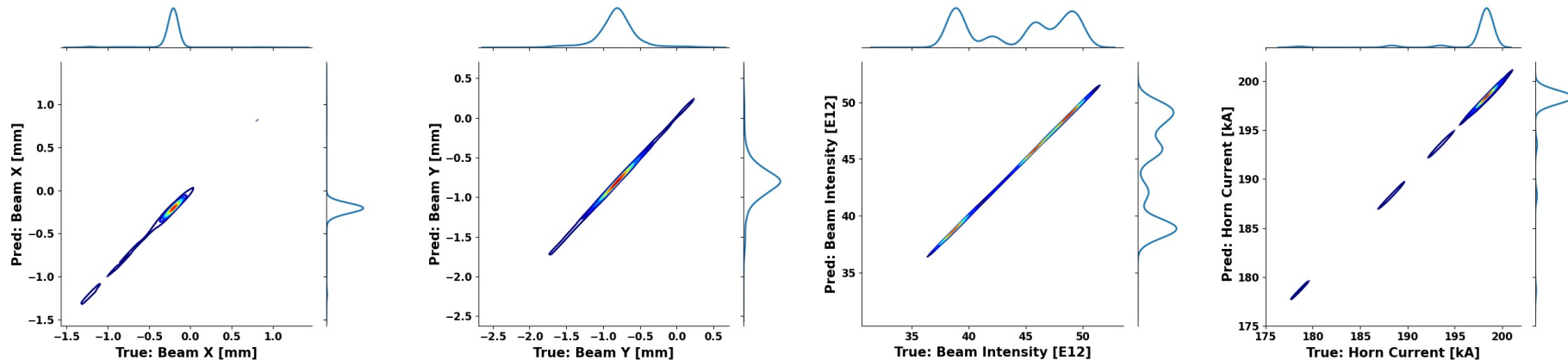
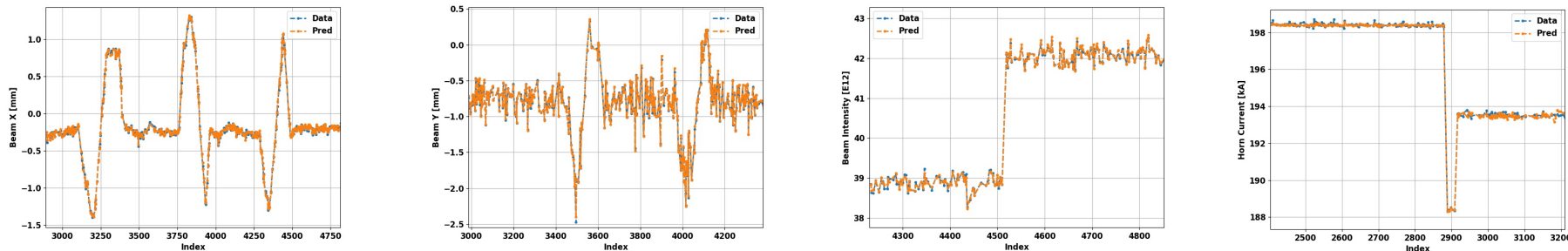# AI / ML for NuMI Target System Monitoring
Example of model predictions

Athula Wickremashinghe, Katsuya Yonehara

Predictions on model validation data

Zoomed view of example predictions

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AI / ML for NuMI Target System Monitoring
Project status

Athula Wickremashinghe,
Katsuya Yonehara

- The tuned model has a good capability of predicting the beam position horizontal and vertical, beam intensity and horn current with the standard error of +/- 0.018 mm, +/-0.013mm, +/- 0.05 E12 and +/- 0.10 kA respectively. **Those are well below the required accuracy of beam related systematic uncertainty.**

- Planning to implement the ML model predictions for daily NuMI beamline data monitoring

- NuMI beam simulation studies are ongoing to predict neutrino flux
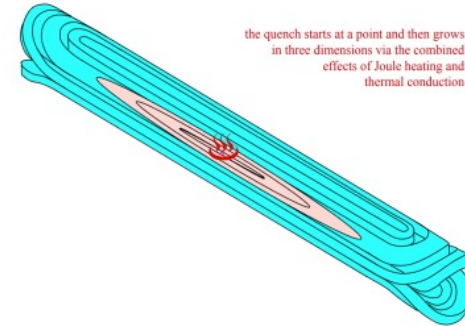
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Real-time quench detection

Duc Hoang, Vittorio Marinozzi, Christian Boffo, Steven Krave, Stoyan Stoynev, Nhan Tran

https://ieeexplore.ieee.org/document/9354037

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Superconducting Magnet Quenches

- In order to maintain superconductivity, superconducting magnets typically operate **at or below liquid helium temperature**.

- Due to several reasons (mechanical imperfections, conductor motions, …), **a specific spot** in the magnet may **heat up**.

- This can eventually cause the whole magnet to **become resistive**. And with huge amount of current pumping through, it can be **catastrophic**.
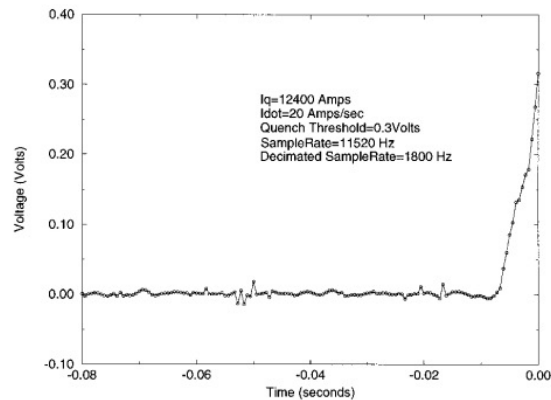

Growth of the resistive zone

the quench starts at a point and then grows in three dimensions via the combined effects of Joule heating and thermal conduction

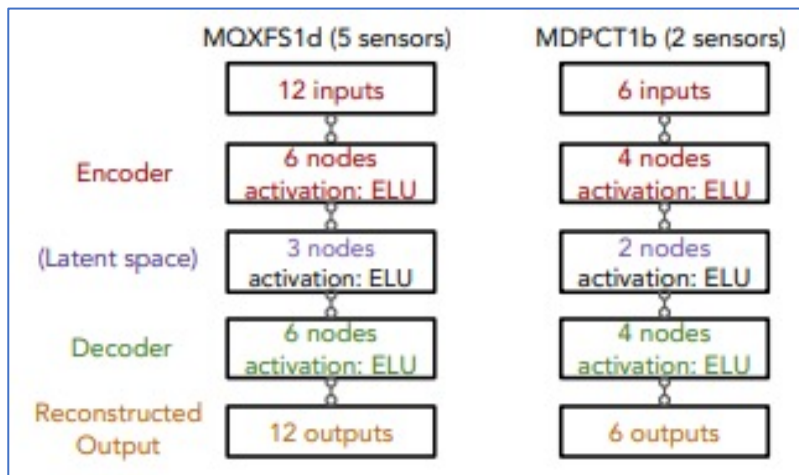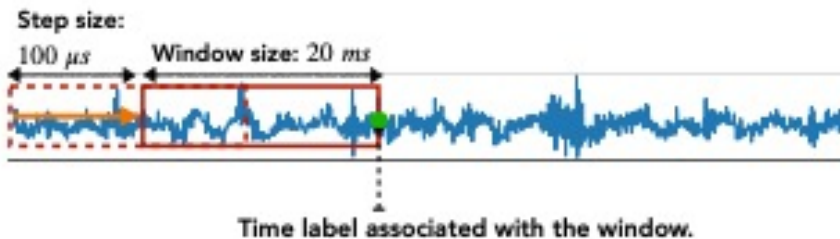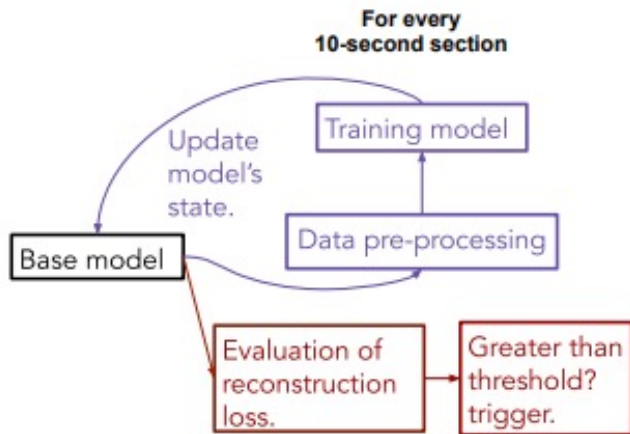Wilson et al. Superconducting magnets for accelerators.

Magnet "training" requires 10s of quench events

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Challenges

- Physics of quenches are not well-understood

- Typically are detected (milli-)seconds after the event happens

- Magnet training is expensive (~$300k, 2 weeks per magnet)

  - future colliders and high TC superconductors even more important

- Can we understand and potentially mitigate quench events?

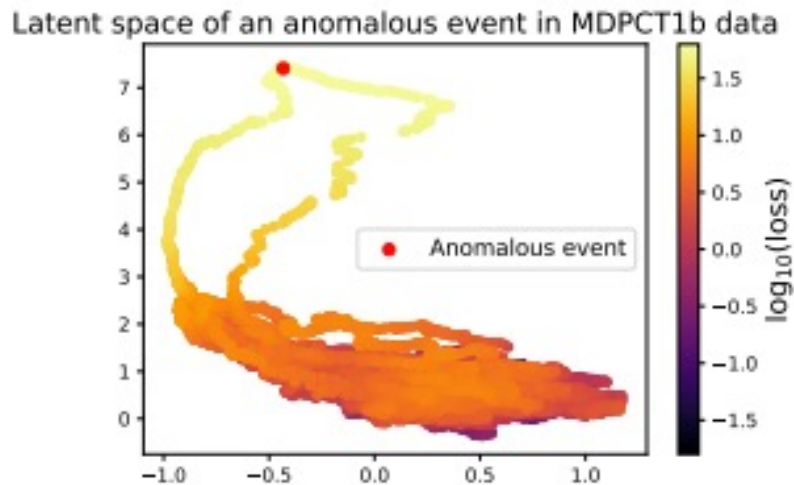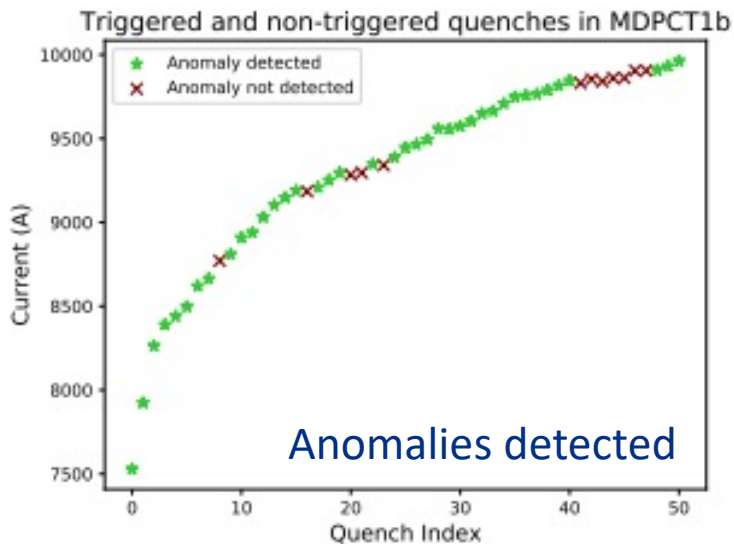- Use (acoustic and other) sensors to detect precursors to the quench

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Anomaly detection with continuous learning

For every
10-second section

Update model's state.

Base model → Training model → Data pre-processing

Evaluation of reconstruction loss. → Greater than threshold? trigger.

Step size:
100 μs

Window size: 20 ms

Time label associated with the window.

"Simple" ML algos using statistical features of time series data

	MQXFS1d (5 sensors)	MDPCT1b (2 sensors)
	12 inputs	6 inputs
Encoder	6 nodes activation: ELU	4 nodes activation: ELU
(Latent space)	3 nodes activation: ELU	2 nodes activation: ELU
Decoder	6 nodes activation: ELU	4 nodes activation: ELU
Reconstructed Output	12 outputs	6 outputs

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Results

Detected 77% of anomalous events ahead of the quench (<15s)

Anomalies detected

Characterizing anomalous events

A lot more interesting data analysis that can be done
and would like to build a real-time platform!

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Closing

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Organizing ourselves for the future

- Many AI projects have been underway in the past few years
  - Lots of opportunities to collaborate with other accelerator laboratories

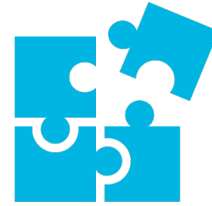- AI for Accelerator Applications Workshop over the coming week will:

Showcase current work on AI/ML for accelerators	Build community	Develop and communicate a shared vision	Identify resources that are needed to empower us to work together and apply AI/ML to accelerators	Evaluate designs for a modernized control system to enable AI/ML

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